Effectiveness of Time-Reversal technique for UWB wireless communications in standard indoor environments

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Abstract

Time-Reversal (TR) technique has opened a new area of investigation for wireless ultra-wide band (UWB) communications applications especially for indoor environments. Such interest is based on the space and time-focusing properties of TR. In high reverberating media with large delay spread, time-focusing induces an equivalent impulse response almost free from side-lobes lowering drastically the risk of Intersymbol Interference (ISI) and allowing much higher data rates. However, in a real channel the delay spread may not be enough to expect such a good performance. We show that in realistic indoor standard environment, the scattering level of the channel is really poor inducing a TR gain collapse to few decibels. These results give an insight of the real effectiveness of TR UWB communications in realistic channels.

1. INTRODUCTION

For the last decade, the development of home and office networks have lead to a major interest for indoor telecommunications. The systems complexity requires higher data transfer rates leading to the use of short symbol durations. A major problem, is that as the bandwidth is enlarged the symbol duration becomes of the same order of magnitude than reverberation time or delay spread due to multipath. The main consequence is the appearance of Intersymbol Interference (ISI) as the distance between symbols becomes shorter than the delay spread time. ISI is an important problem to overcome, especially in UWB communications where the symbol length is likely very short compared to the spreading time.

A way to minimize the ISI problem, is the use of Time-Reversal (TR) technique [1,2]. The main idea is analog to the matched-filter approach where the channel is viewed as a filter to match to. The emitted signal is therefore pre-filtered by the time-reversed channel impulse response in order to match to the channel. The consequence in an indoor context is a compensation of the reflected waves that take place in the real channel. The compensation is all the more effective that the channel is rich of scattering. This feature has lead many works to focus on the use of TR technique for wireless communications [3,4]. However most experiments, to our knowledge, have been performed in highly reverberant media [1-3] with such a large reverberation time that it is far from realistic indoor environments. In the strong reverberation case, it is clear that TR is of great interest. However, most indoor communications do not work in such environments but rather in standard offices which do not present in many cases a high delay spread. The aim of this paper is to point out the link between the TR gain and the indoor channel parameters such as the delay spread. To carry out this study, we have performed measurements in various indoor environments providing a wide range of delay spreads values; from these experimental data we assessed the TR effectiveness for indoor wireless communications in standard environment.

We shall recall briefly in section II the basic theory of TR technique applied to indoor channels. In section III, we will present the measurement setup and the different indoor environment samples. In section IV we shall present the post-processing procedure and the results obtained from the experimental data.

2. TR basic theory for indoor channels

We adopt the classical channel modeling approach for indoor communications based on the use of tapped delay lines model. Hence the channel impulse response *h(t)* can be expressed as,

$$h(t) = \sum_k \alpha_k \delta(t - \tau_k) \quad . \tag{1}$$

where α_k and τ_k are respectively the amplitude and the instant of the echoes peak.

The time-reversal technique principle is to convolve the signal *x(t)*, the signal that we wish to recover on the receiver, with the time-reversed channel impulse response *h(-t)*, leading to the following injected signal $x_{TR}(t)$ (at the emitter) defined as,

$$x_{TR}(t) = x(t) * h(-t) \tag{2}$$

where (*) stands for the convolution operation. Note that in practice, the use of TR will lead to increase the emitter complexity since it assumes a knowledge *a priori* of the impulse response *h(t)* of the channel before transmitting the real signal.
The transmission of $x_{TR}(t)$ leads to a received signal *y(t)* that stands as,

$$y(t) = h(t) * x_{TR}(t) = g(t) * x(t) \qquad (3)$$

where *g(t)* is the equivalent impulse response including the pre-processing matched filter *h(-t)* and the channel response *h(t)*. The convolution *h(t)* and *h(-t)* is equivalent to the autocorrelation function of *h(t)* i.e of the real channel impulse response. In order to recover *x(t)*, the ideal case is to have *g(t)* made of a single Dirac whereas *h(t)* is composed of a large amount of echoes – this feature is commonly referred as *pulse-compression* property of TR technique. The equivalent filter can be therefore expressed as,

$$g(t) = h(t) * h(-t) = \sum_k \beta_k \delta(t - \tau'_k) \qquad (4)$$

where the weights β_k are related to the amplitudes of the impulse response as follows,

$$\beta_k = \sum_{i,j} \alpha_i \alpha_j = \sum_i \alpha_i^2 + \sum_{i \neq j} \alpha_i \alpha_j \qquad (5)$$

and the instant τ'_k are defined as,

$$\tau'_k = \tau_j - \tau_i \qquad (6)$$

The present model does not take into account the dispersive character of the channel and of the antenna involved in the transmission and can whence be viewed as simplistic. However, it provides a good insight of the role of the scattering and of the number of echoes in the TR effectiveness. In a first approach, if the echoes in the channel are considered as independent variables and there amplitudes α_i are described by a probability density function centered on zero we can expect the $\alpha_i\alpha_j$ sum of equation (5) to vanish. This implies that the autocorrelation function *g(t)* would reduce to a single Dirac whose energy includes the total energy of the initial impulse response *h(t)*.
However, in indoor standard environments the impulse response might include only few echoes as shown in Fg.1a that leads to a normalized *g(t)* composed of remaining echoes as illustrated in Fig.1b. The given example is taken from a simulation result but has the benefit to point out the importance of the echoes sign repartition in the channel response. Indeed, we have computed the autocorrelation function taking into account |h(t)| (shown in Fig.1b and Fig.1a respectively). We can clearly see that the side-peaks leading to the ISI phenomenon is much higher when all the α_i are of the same sign (here positive). The impressive pulse-compression observed by Fink and co-workers [1,2] in high reverberating media may not be so effective on the ISI problem of realistic indoor environments. To quantify the effectiveness of TR we introduce a peak SNR on the autocorrelation function, defined as the ratio between the desired peak and the maximum of the undesirable peak (see Fig.1b), as follows,

$$SNR = 20log\left(\frac{g(0)}{max(g(t))_{t\neq 0}}\right) \qquad (7)$$

In order to see more precisely the effectiveness of TR technique in standard channels, we have measured experimentally the impulse response of various indoor environments that we shall present in the next section.

3. Experimental setup

We have performed measurements in various indoor places. The places were chosen on the base of the delay spread. The aim was to have a large range of delay spread values in order to see the possible link between it and TR effectiveness. To carry out this aim, we have chosen three indoor classes. The first one is the reverberant chamber (RC) (3.08m×1.84m×2.44m) with variable losses inserted in it to vary the delay spread. The second class is the room that includes the RC (as shown on Fig.2). The partial metallic walls allow a reverberation level that leads to what we would call an in-between delay spreads range values. The third class includes two realistic standard indoor environments : a 2-meters wide corridor made of plasterboards and a hall (as shown on Fig.3) made of concrete walls. In both cases the ceiling is made of metallic paneling. A line-of-sight (LOS) and a non-line-of-sight (NLOS) configuration has been performed in the hall case; whereas, a LOS configuration has been carried out in the corridor case.

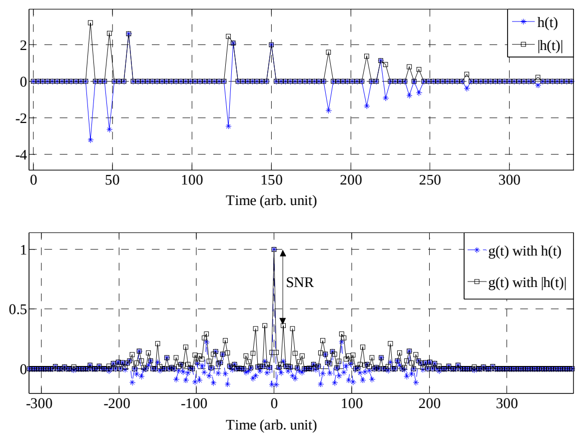

Fig. 1. (a) Example of a channel response *h(t)* with fifteen α_i and its absolute value |*h(t)*|. (b) Respective computed normalized autocorrelation function. The influence of the sign repartition of the α_i has a direct influence on the side-peaks amplitudes.

In order to perform these measurements we used the following experimental setup : a vectorial network analyzer (ZVB8 R&S), a log-periodic antenna and a phase-sensitive optical probe (EFS-105 ENPROBE). The measurements were carried out from 700MHz to 6GHz. In order to take advantage of the whole bandwidth we used the arbitrary central frequency of 3.35GHz. As we were interested in assessing the influence of the bandwidth on TR performance, we have chosen the three following values : 1GHz, 3GHz and 5.3GHz.

In order to estimate (by post-processing) the influence of the channel response on TR effectiveness, we have characterized the antenna free-space pulse response $y_{FS}(t)$ in an anechoic chamber (AC) using a [700MHz:6GHz] bandwidth. In Fig.4a we present the equivalent channel model associated to the antenna characterization, where $h_A(t)$ and $h_P(t)$ are the impulse response of the antenna and of the optical-probe respectively.

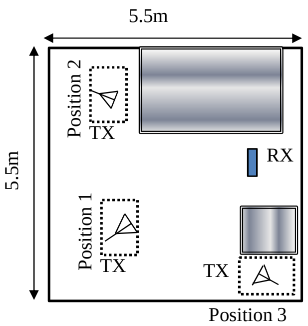

Fig. 2. Disposition of the antenna and the probe outside of the RC. Position 1 is LOS whereas position 2 and 3 are NLOS.

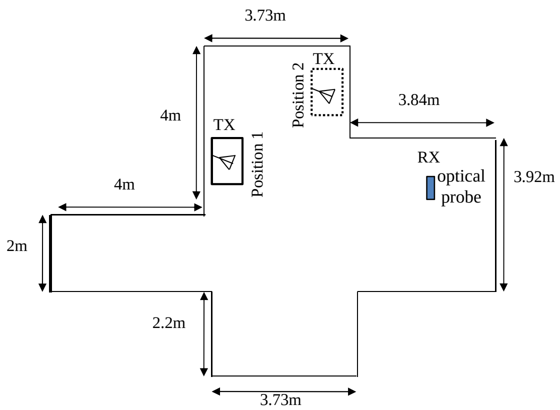

Fig. 3. Dimensions of the hall made of concrete walls and metallic panelling ceiling. The antenna and the VNA are on a cart placed on position 1 and 2 for line-of-sight (LOS) and non line-of-sight (NLOS) measurements respectively. The optical probe is fixed and connected by an optical fiber to the cart.

4. Post-processing and results

The aim of the post-processing is to assess the autocorrelation function of the real channel response to quantify in a clear way the SNR introduced in section 2 and therefore the effectiveness of TR technique for indoor environments.

To make a clear distinction of the influence of the channel we model the transmission as shown in Fig.4b where $h_C(t)$ stands for the impulse response of the real channel. Note that to simplify the approach we assume that the antenna has an impulse response independent of the direction of the multipath. We use the antenna characterization model to simplify the indoor transmission model as shown in Fig.4b.

Ideally we should compute the channel response $h_C(t)$ by some deconvolution method and compute the $g(t)$ function of section 2. Instead, recalling that the aim is a measure of the influence of $h_C(t)$ on the effectiveness of TR technique, we shall compute and compare the autocorrelation $R_{yy(t)}$ of $y(t)$ and the cross-correlation function $R_{y,y_{FS}}(t)$ of $y(t)$ and $y_{FS}(t)$. Indeed, the two formers functions can be expressed respectively as,

$$R_{y,y}(t) = h_c(t) * \left(h_c(-t) * \left(y_{FS}(t) * y_{FS}(-t)\right)\right) \qquad (8)$$

and,

$$R_{y,y_{FS}}(t) = h_c(t) * \left(y_{FS}(t) * y_{FS}(-t)\right) \qquad (9)$$

It appears that the $R_{y,y}(t)$ function is a measure of the transmission using TR applied to the channel impulse response whereas the $R_{y,y_{FS}}(t)$ function is a measure of a conventional transmission. In both cases, the autocorrelation of $y_{FS}(t)$ corresponds to the virtual injected signal. The SNR introduced in section 2 is then applied to the functions given by equation (8) and (9) in order to assess the gain provided by TR technique.

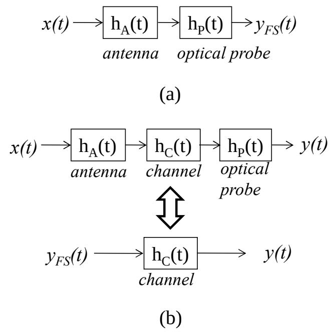

Fig. 4. (a) Channel transmission model in a AC. (b) Simplification of the transmission model of the measurements performed indoor using the AC channel model.

4.1. Delay spread

A measure of the reverberation of the medium is given by the delay spread T_{RMS} of the impulse response. A -40dB threshold has been chosen to define the T_{RMS}, as the delay spread time (as shown in Fig.5a). In the cases that we consider this parameter varies almost over two orders of magnitude. We show in Fig.5 the impulse response in the RC with no absorbers and in the hall respectively.

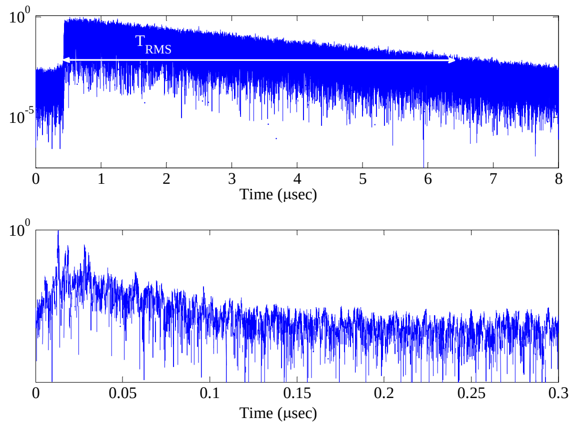

Fig. 5. Impulse response (a) in the RC with no absorbers (b) in the hall

4.2. Results

The aim of this section is to assess the effectiveness of the TR technique. To perform such estimation we plot in Fig.6 the different TR SNR (in linear not in dB for clarity convenience) using the functions given in equation (8), as a function of the different delay spreads taken down from the different configurations. We apply the procedure for the three different bandwidths. We find back that the TR SNR in a RC is all the more efficient than the bandwidth is large as described in ref [1] and [2] up to a certain limit [5] that is not reached in the present work.

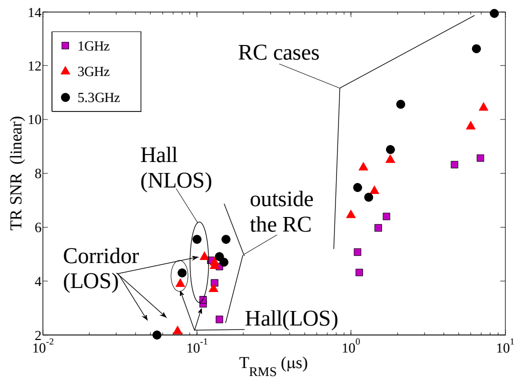

Fig. 6. The TR SNR versus the delay spread T_{RMS} computed in the different configurations.

For standard indoor environments however, the TR SNR is much lower especially in the corridor LOS case. This is due to the poor reverberation level leading to a non-zero mean of echoes weights as illustrated in section 2. To compare and assess the interest of TR in indoor channel we have plotted the gain provided by TR with respect to a conventional transmission. We show the results in Fig.7 where we find back the high gain provided by TR in high reverberating environment but a gain of a few dB only for standard indoor channel as the hall LOS and corridor LOS cases. We observe a gap of about 22dB with the best RC case. The latter is often taken as a reference in the litterature and may mislead on the actual effectiveness that can perform TR technique on the ISI problem in a real indoor channel.

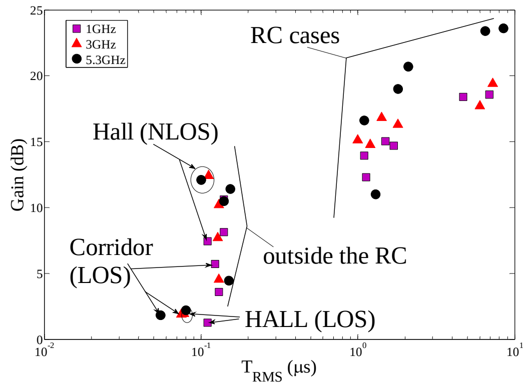

Fig. 7. The SNR Gain provided by TR technique compared to conventional transmission.

5. CONCLUSION

We have performed a series of measurements in various indoor environments covering a large range of delay spread values. These have confirmed the good effectiveness of TR technique in high reverberating media and the link between the bandwidth and the TR gain. However, for standard indoor channels we observe a TR gain collapse. TR technique in those cases may not be as effective as expected in ref [1] and [2]. The present work gives a more realistic insight of the relative ability of TR to reduce the ISI problem in real indoor UWB transmissions.

6. REFERENCES

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